Renewable and Sustainable Energy Reviews 15 (2011) 3045–3050

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A comprehensive review on solar water heaters

S. Jaisankar[a,*], J. Ananth[b], S. Thulasi[c], S.T. Jayasuthakar[c], K.N. Sheeba[d]

[a] Star Lion College of Engineering & Technology, Thanjavur, Tamilnadu 614206, India
[b] Department of Mechanical Engineering, Roever Engineering College, Perambalur, Tamilnadu 620 009, India
[c] Department of Mechanical Engineering, Anna University of Technology, Thirukuvalai Campus, Tiruvarur, Tamilnadu, India
[d] Department of Chemical Engineering, National Institute of Technology, Trichy, Tamilnadu 620015, India

ARTICLE INFO

Article history:
Received 13 May 2010
Accepted 19 August 2010
Available online 11 May 2011

Keywords:
Solar water heater
Thermal performance
Heat exchangers
Twisted tapes
Aero profile
Variable headers

ABSTRACT

Solar water heating system proves to be an effective technology for converting solar energy into thermal energy. The efficiency of solar thermal conversion is around 70% when compared to solar electrical direct conversion system which has an efficiency of only 17%. Hence solar water heaters play a vital role in domestic as well as industrial sector due to its ease of operation and simple maintenance. Extensive works on improving the thermal efficiency of solar water heaters resulted in techniques to improve the convective heat transfer. Passive technique has been used to augment convective heat transfer. These techniques when adopted in solar water heaters proved that the overall thermal performance improved significantly. This paper reviews various techniques to enhance the thermal efficiency in solar water heater. In addition to this, a detailed discussion on the limitations of existing research, research gap and suggested possible modifications is made.

Contents

1. Introduction

Flat plate collector is the central component of any solar water heating system. The efficiency of a solar water heating system is based on the performance of flat plate collector. Hence, the most of the research work has been focused on the performance improvement of flat plate collector. The characteristics of thermosyphon systems are based on the absorber plate and its design, selective coatings, thermal insulation, tilt angle of the collector, working fluids and have been analyzed by many researchers. It has been described in detail in the review of solar water heaters. Similarly, the effect of twisted tapes, twist geometry on the performance improvement of solar water has also been discussed in the review.

* Corresponding author. Tel.: +91 4374 243243; fax: +91 4374 244244.
E-mail address: jaisankar13@yahoo.com (S. Jaisankar).

1364-0321/$ – see front matter © 2011 Published by Elsevier Ltd.
doi:10.1016/j.rser.2011.03.009

2. Solar water heaters

Solar water heaters are characterised by its thermal performance and it largely depends on the transmittance, absorption and conduction of solar energy and the conductivity of the working fluid. The schematic layout of a typical thermosyphon solar water heater is shown in Fig. 1. The cross sectional view of a solar water heater is shown in Fig. 2.

The design parameters such as plate efficiency factor (F') and heat removal factor (FR) have been analyzed by Hottle and Whiller [1] and they significantly reduced the empiricism associated in the design of solar collectors. Further, Bliss [2] proposed mathematical derivations for several efficiency factors for various types of collectors, together with graphical data. Similarly, the collector efficiency and loss factors in solar air heaters have been analyzed mathematically by Parker [3] and equations are developed. These equations enable the designers to predict the collector performance for a

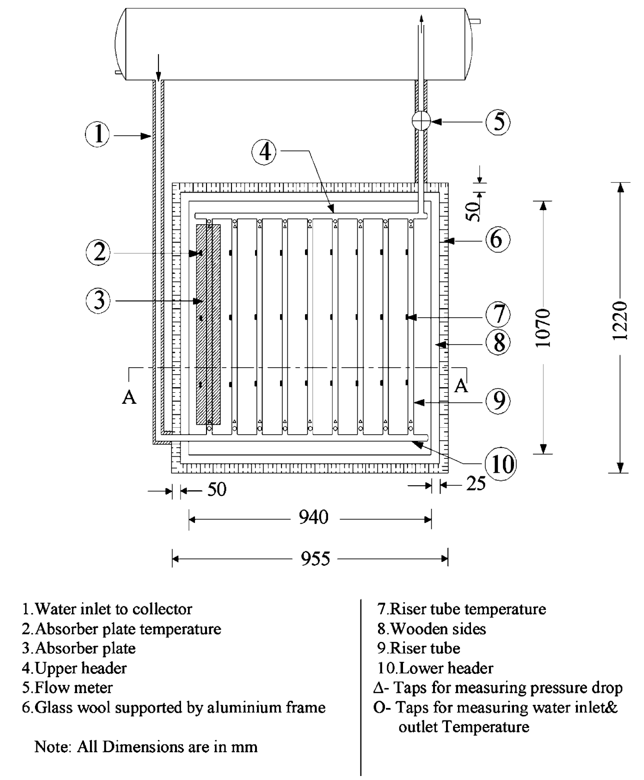

Fig. 1. Schematic layout of a typical thermosyphon solar water heater.

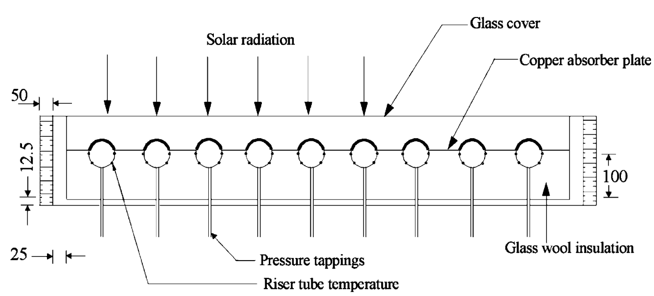

Fig. 2. Cross sectional view of the solar water heater.

selected flow rate and environmental conditions. Thermal performance of collector is also dependent upon the optical efficiency of glass cover, design and thermal properties of the absorber plate. The maximum energy conversion of absorber plate using selective coatings to reduce radiative losses has been analyzed by many researchers [4–6]. Further, the effect of thermal conductivity of the absorber plate on the performance of solar collectors has been studied through the transient simulation system (TRNSYS) by Shariah et al. [7] and they confirmed that the characteristic factors like fin efficiency factor, collector efficiency factor and heat removal factor are strongly dependent on the thermal conductivity of absorber plate.

The effect of annular space between riser tube and absorber plate on the thermal performance of solar collector has been analyzed experimentally and theoretically by many researchers [8–12]. A good contact between the riser tube and absorber plate is found to increase the thermal performance and has been analyzed experimentally by Whiller and Saluja [13] and their findings proved that the efficiency factor (F') of collector increased from 0.77 to 0.89 for soldered bond instead of unsoldered bond.

The effect of various designs of absorber plate on the performance of a solar water heating system has been investigated in due course. Mittal et al. [14] analyzed the use of artificial roughness on a surface to enhance the rate of heat transfer to fluid flow in the duct of a solar air heater. Comparison of effective efficiency of solar air heaters having different geometries of roughness elements on the absorber plate has been analyzed. Results showed that the inclined ribs as roughness element exhibits effective efficiency that increased with increase in Reynolds number. This finding inspired further research on cross corrugated design of the absorber plate. The improvement in the efficiency of solar air heater by cross-corrugated absorber plate which enhances the turbulence and heat-transfer rate inside the air flow channel has been analyzed by Gao et al. [15]. Results proved that cross-corrugated solar air-heaters have better thermal performance when compared to flat-plate collector. Yet another breakthrough is the use of Vee-shaped absorber plate to improve the convective heat transfer and this has been analyzed experimentally and numerically in both natural and forced circulation mode [16–21].

The effect of geographical conditions, collector orientation, tilt angle and material of fabrication on the output of a solar collector system has been studied. Rabel [22] and Andersen [23] analyzed these aspects and illustrated the effect of these parameters on the thermal performance of the system. Similarly the effect of dust accumulation on the glass cover of solar collector has been investigated experimentally with different tilt angles by Hegazy [24]. The results indicated that the fractional reduction in glass transmittance depends on dust deposition in conjunction with plate tilt angle, exposure period and site climatic conditions. Empirical correlations have been developed and fitted with experimental data within an uncertainty of $\pm 6\%$ and these results have been found to be useful for the design of solar water heaters. Similarly, the effect of dust accumulation in solar collectors with various tilt angles from 0 to 90° has been studied experimentally by Soulayman [25]. The results of his experiment concluded that 0° tilt angle is most contaminated with a mixture of coarse and fine dust particle and 90° tilt angle has least amount of dust accumulation.

Storage tank is an integral component in thermosyphon solar water heater system, and the thermal energy is extracted from the storage tank. Experimentation has been carried out to minimise the losses from storage tank by proper insulation using various materials of varying thickness by Colle et al. [26]. Thermal performance of solar collector with storage tank has been analyzed numerically and models have been developed by Brinkworth [27] and Andres and Lopez [28]. Thermal stratification in storage tank is the driving mechanism for thermosyphon solar water heater which has been analyzed experimentally and numerically by many researchers [29,30]. Results revealed that heat removal efficiency of thermosyphon solar water heater is highly dependent on thermal stratification. Further experimental studies have been carried out by Chang [31]. He evaluated the heat removal efficiency during the system application phase. Physical heat removal patterns have been identified and empirical models have been developed. This study established a storage tank design which enables the characteristic heat removal efficiency of the complete system to be optimized.

The thermosyphon solar water heaters works on the buoyancy force created in the storage tank that is determined by the mass flow rate of collector loop. Numerous works on the performance of solar water heaters with various operating parameters have been undertaken by many researchers [32–37]. Mass flow rate increases proportionate to the height between the collector and storage tank and this effect on the performance of the system has been analyzed experimentally by Guptha and Garg [38]. Zerrouki, Duffie and Beckman [39,40] made several assumptions regarding mass flow rate of collector like neglecting the headers area, uniform distance between riser tubes, laminar flow and uniform distribution of flow in the tubes and these assumptions proved to be useful

for the design of thermosyphon system. Similarly, Zerrouki et al. [41] have analyzed the characteristics of natural circulation system such as mass flow rate, temperature rise of fluid and absorber plate temperature and validated the experimental results with the theoretical model. Further, Karaghouli and Alnaser [42] have studied the performance of the thermosyphon water heater unit for several sunny and cloudy days. Experiments have been carried out for several months and parameters like solar insolation, inlet and outlet temperature of water, useful energy collected by the system and instantaneous efficiency of the system, average energy collected by the systems have been discussed. The overall performance rating of a thermosyphon solar water heater considering the thermal performance of the system during the energy-collecting phase and the system cooling loss during the cooling phase has been analyzed experimentally by Chang et al. [43]. The performance rating of collector has been found to be related to the heat removal efficiency of the system during the application phase. This study evaluates the thermal performance and heat removal efficiency for 12 systems with capacities in the range of 102–446 L. The experimental results have been validated with simulation study. Belessiotis and Mathioulakis [44] have conducted experiments on thermosyphon solar water heaters and compared the results with the simulation results. The proposed methodology has been found to be useful in the system design phase to optimize the performance. Similarly, the performance of hot water system has been analyzed experimentally and results validated using simulation by Henden et al. [45].

Working fluid in a solar collector system plays a vital role in heat augmentation studies, because the solar energy is converted to useful form of thermal energy by the working fluid. The two-phase closed thermosyphon (TPCT), called gravity heat pipe, has been used in solar water heating system. In this a heat pipe has been included in the storage tank of a solar water heater and the performance studies using various working fluids like water, methanol, acetone and ethanol have been conducted [46–52]. The thermal performance of a two-phase thermosyphon solar collector with different refrigerants (R134A, R407C, and R410A) has been analyzed in three identical small-scale solar water heating systems under various environmental conditions by Esen and Esen [53]. Results proved that R410A refrigerant has higher energy collection performance than the other refrigerants. Further, the thermal behaviour of two-phase closed thermosyphon with an unusual geometry such as semicircular condenser and a straight evaporator have been analyzed experimentally by Abreu and Colle [54]. Different lengths of evaporator fill ratio of working fluid, cooling temperature and slope of the evaporator have been tested for different heat fluxes, and the effects of these parameters on the overall thermal resistance have been verified. These steady state transient results are useful in the design of compact solar domestic hot-water system. Experimentation has been carried out by Joudi and Al-Tabbakh [55] in a similar way and they compared the experimental results with the simulation results.

Several designs of solar collectors have been experimented to elucidate the thermal behaviour of thermosyphon systems. The thermal performance of trapezoidal-shaped solar collector assembly has been found to be influenced by thermal stratification. It has been studied experimentally by Cruz et al. [56]. This trapezoidal cross-section induces thermal stratification in the water store and provides sufficient energy storage to meet the daily hot-water demand. These experimental results have been validated by simulation studies. Results revealed that total energy-saving by this trapezoidal design were around 30–70%.

Cost accounted for fabrication of solar water heater is one the major factor in economic analysis. Chaurasia [57] carried out experiments to design and develop a low cost solar water heating system using cement concrete. The temperature of hot water obtained in this study varied from 36 °C to 58 °C. This type of collectors is very useful for low temperature household applications. This can be used by architects for designing the roof of the building which may serve as a low cost solar collector to provide hot water at moderate temperature in buildings for meeting various purposes during daytime.

3. Heat argumentation techniques

Extensive works have been carried out for heat transfer augmentation by active and passive techniques. A detailed review on the use of active techniques like electric field, vibration, acoustic and passive technique like special surface geometries, viz., twisted tapes, curved tubes, helically coiled tubes, spirally coiled tubes to improve the heat transfer has been performed by Naphon [58]. Comparing the above techniques, passive method has been found to have better heat enhancement with out the aid of any external energy. Among the various elements in passive techniques twisted tapes are found to be effective in convective heat transfer augmentation. Twisted tapes create swirl flow and increase the heat transfer and pressure drop of the system and this has been analyzed by many researchers [59–67]. Smithberg and Landis [68] have developed an analytical model of the flow mechanism for the fully developed turbulent flow through tubes with twisted-tape swirl generators. The velocity field is helicoidal with the creation of swirl flow and secondary flow is superimposed. Hence, the fluid moves in both axial and tangential direction. The frictional losses are calculated from the axial and tangential boundary layer flow. Heat transfer and pressure drop characteristics of tube fitted with twisted tape and water (single-phase fluid) as a working fluid has been studied experimentally by Lopina and Bergles [69]. Results revealed that twisted tape increases hydraulic length, creates centrifugal force and fin effect. It has been found that heat enhancement is around 20% higher than the plain tube.

Improvement in heat transfer performance by inserting twisted tape in double pipe heat exchanger has been analyzed experimentally by Sivashanmugam and Sundaram [70]. Experimentation has been carried out for twist ratio of 4.149, 4.95, 5.882, 8.54 and 15.699 with Reynolds number starting from 3000. The results confirmed that the maximum percentage of energy transfer rate is nearly 44.7% with a minimum twist ratio 4.149. The overall thermal performance has been found to be better in minimum twist ratio compared to other ratios for a given Reynolds number. The wall shear and the temperature gradients leading to heat transfer augmentation from tube wall have been analyzed by Sarma et al. [71]. The modified friction and heat transfer coefficient for tube fitted with twisted tape have been predicted to be in laminar regime. The role of eddy viscosity due to the presence of twisted tape has been found to be more dominant over kinematic viscosity. Further, the heat transfer and pressure drop characteristics of horizontal pipe with twisted tape insert has been investigated by Naphon [72]. Experimentation has been carried out with aluminum twisted tape having thickness of 1 mm and a length 2000 mm. Cold and hot water are used as working fluids in shell side and tube side respectively. Mass flow rate ranging between 0.01 and 0.7 kg/s and between 0.04 and 0.08 kg/s respectively has been used. Results for twisted tape inserts proved that the heat transfer is higher than in plain tube. Similarly, the isothermal friction factor and the Nusselt number correlations have been developed by Kang et al. [73] for tube fitted with twist insert. Based on the experimental results, mathematical models have been developed to predict the friction factors for a fully developed turbulent flow in a spirally corrugated tube combined with a twisted tape insert by Zimparov [74]. The flow field has been divided into two principle regions namely helicoidal core flow and the secondary flow and swirl mixing due to wall rough-

ness. Around 87.7% of the calculated friction factors have relative difference of less than ±15%.

Works involving improvement in design and geometry of twisted tapes for improving the heat transfer effect is numerous. In this regard, experiments have been carried out by Eiamsa-ard and Promvonge [75] for twisted tape with centre core rod and without centre core rod. Experimentation has been conducted with the range of Reynolds number from 2000 to 12,000. The average Nusselt number in helical tape with and without core rod indicated an increase of around 230% and 340% compared to plain tube. The heat enhancement efficiency of the helical screw-tape varied between 1.00 and 1.17, 1.98 and 2.14 for the tapes with and without core-rod respectively. Similar configuration of helical screw twisted tape inserts has been analyzed for both laminar and turbulent regime by Sivashanmugam and Suresh [76,77]. Helical screw tape with different twist ratios, increasing and decreasing order of twist has also been considered in this study. Results indicated that heat enhancement is always higher in helical screw tape than the plain tube and there is not much change in magnitude of heat transfer coefficient enhancement while increasing (or) decreasing twist ratio. Empirical correlation developed for Nusselt number and friction factor have been fitted with experimental data with in the range of ±15% and ±13% respectively. The effect of tube geometry on the heat transfer area has been studied by many researchers. The heat transfer and turbulent flow friction characteristics in a circular wavy-surfaced tube under constant heat flux condition with a helical-tape insert has been analyzed experimentally by Eiamsa-ard and Promvonge [78]. The turbulent flow near the tube wall is produced by wavy surface and swirl flow is generated by helical-tape. Experiments have been carried out in the range of Reynolds number from 300 to 9200. It has been observed from the results that the Nusselt number and friction factor for wavy surface wall are 3.0 and 50 times over that of the plain tube respectively. Similarly, for tube combined with wavy surfaced wall and the helical tape, Nusselt number and friction factor increase by 4.2 and 110 times than that of the plain tube respectively. It is found that the wavy surface tube combined with helical tape provides higher heat transfer and friction factor than the wavy surface tube alone. Heat transfer, friction factor coefficients of plain, micro fin and twisted tape insert tube have been analyzed by Al-Fahed et al. [79]. Twisted tapes with different twist ratios and with tight and loose fit have been studied. Experiments have been carried out in laminar regime using steam as the heating source. Results revealed that heat transfer and pressure drop increase in the order of use of plain tube, microfin and twisted tape respectively. Here, the maximum heat and pressure drop has been obtained for twisted tape with minimum twist ratio. The maximum heat and pressure drop has been observed in loose fit compared to tight fit with minimum twist ratio. This is because the fluid has swirl effect in loose fit in addition to the vibration of fluid particles. The heat enhancement in a tube fitted with serrated twisted tape with twist ratio 1.56, 1.88 and 2.81 has been analyzed by Chang et al. [80]. Experimentation has been carried out for the wide range of Reynolds number from 5000 to 25,000. The heat enhancement in serrated twisted tape is 250–480% compared to plain tube. This is 1.25–1.67 times higher than the tube fitted with smooth twisted tape. For the same pumping power, thermal performance of serrated twisted tape and smooth twisted tape has been compared.

Further, the experimental investigation of heat transfer and friction factor characteristics of circular tube fitted with right–left helical screw inserts of equal and unequal length of different twist ratios have been studied by Sivashanmugam and Nagarajan [81]. The results revealed that the heat enhancement is higher in right–left twist compared to straight helical twist. Empirical correlations have been developed for Nusselt number and friction factor and are fitted with experimental data with in ±10% and 20% respectively. Similarly the effect of right–left helices has been studied by many researchers [82–84]. The heat transfer and friction factor characteristics of double pipe heat exchanger fitted with clockwise and counter clockwise arrangement of twisted tape have been analyzed experimentally by Silapakijwongkul et al. [85]. The experiments were conducted for twist ratio of 0.4, 0.6 and 0.8 with Reynolds number varied from 2200 to 11,500. The increased heat transfer rates for clockwise–counter clockwise and helical twisted tape are found to be 219% and 204% when compared with the plain tube. The increased friction factor for the same is around 4.7 and 1.5 times higher than the plain one.

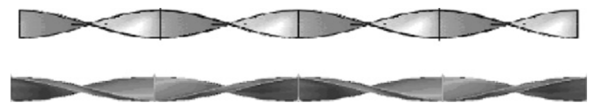

Fig. 3. Various designs of twisted tape insert (helical, left–right).

Twisted tapes are used not only in heat exchanger, but also in solar water heater to improve the convective heat transfer. Various designs of twisted tape elements are shown in Fig. 3 (helical and left–right).

It has been experimentally verified for the first time by Kumar and Prasad [86] in forced circulation mode. Experiments have been carried out for various mass flow rates and twist ratio. Heat transfer and pressure drop in twisted tape collectors have been found to increase by 18–70%, and 87–132%, as compared to plain tube collectors. Empirical correlations have been developed for Nusselt number and friction factor and are fitted with experimental data. Results indicated that twisted tape collectors are preferable for higher grade energy collection and increase in the thermal performance and is around 30% more compared to the plain one. The performance of twisted tape collectors is found to be remarkable at higher values of solar radiation. The above studies have been carried out in series flow pattern in the solar collector. Compared to series flow pattern, parallel flow has a better performance with improved thermal efficiency has been addressed by Rai [87]. Jaisankar et al. [88] studied the heat transfer and friction factor characteristics

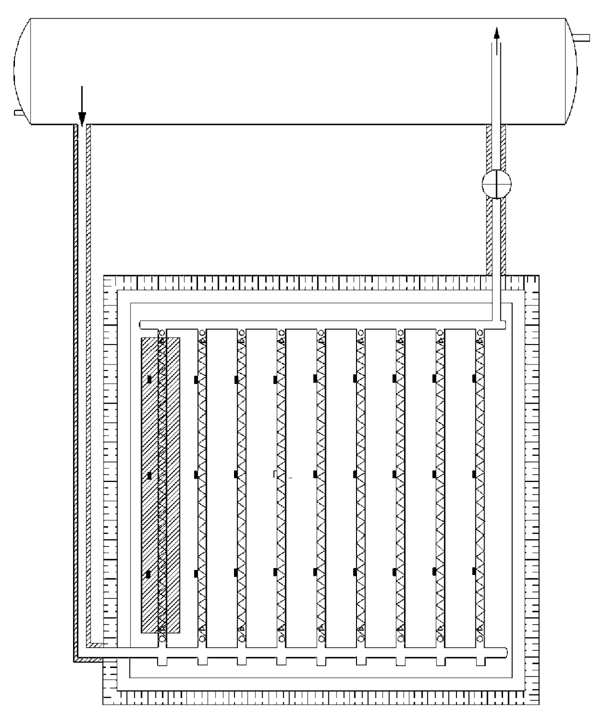

Fig. 4. Thermosyphon solar water heater fitted with twisted tapes.

of thermosyphon solar water heating system fitted with helical twisted tape. The experimental system is shown in Fig. 4. The results proved that the friction factor increases with twisted tape inserts and also there is a significant increase in the heat transfer which ultimately increases the efficiency of the system. Experimental studies on left–right helical twisted tape inserts concluded that the overall thermal efficiency of the system is more for left–right twists when compared to helical tapes [89].

4. Discussion

Twisted tape has been used as one of the passive techniques to augment the heat transfer. It has been widely used in heat exchangers but their applications in solar water heaters are limited.

(1) Solar water heaters works under both natural and forced circulation mode. From the view point of utilization, thermosyphon solar water heater occupies a good position in domestic applications due to its ease of operation without the aid of any external energy. But, as observed from the literature, most of the research works have been conducted in forced circulation mode only.
(2) The performance of parallel flow solar collectors is better than the series flow collectors. But, research work in parallel flow is limited.
(3) In conventional solar water heaters, water is distributed by the uniform headers to riser tubes. But the fluid velocities in riser tubes are not equal.
(4) The effect of convective heat loss due to the movement of atmospheric air over the glass surface had never been discussed.

5. Conclusion

A detailed literature survey on solar water heaters has been performed and it gives a concise overview of the developments in the key areas of technologies to either improve the performance of the present system or to design a new system. The following are the outcome of the review.

(1) More researches may be initiated in thermosyphon solar water heaters to improve the performance.
(2) Research work in parallel flow will improve will give a new insight into the thermal performance.
(3) Variation in flow velocity of the working fluid in the riser tubes can be made uniform using variable headers.
(4) The convective heat loss from the glass cover may be reduced using a suitable aero profile design that will prevent the movement of air over the glass surface.

By implementing the above said modifications in parallel flow solar water heaters the overall efficiency of the system can be improved. Hence the overall conversion loss of the system decreases which would increase the utilization.

References

[1] Hottle HC, Whiller A. Evaluation of flat-plate solar collector performance, vol. 2. Transaction of Conference on the Use of Solar Energy, University of Arizona; 1958 p. 74–104.
[2] Bliss WR. The derivations of several plate-efficiency factors useful in the design of flat-plate solar heat collectors. Solar Energy 1959;3(4):55–64.
[3] Parker BF. Derivation of efficiency and loss factors for solar air heaters. Solar Energy 1981;26(1):27–32.
[4] Hutchins MG. Spectrally selective solar absorber coatings. Applied Energy 1979;5(4):251–326.
[5] Lampert CM. Coatings for enhanced photo thermal energy collection, 2nd non-selective and energy control films. Solar Energy Materials and Solar Cells 1979;1:319.
[6] Cost worth JL, Raghunathan K. Development of selective surfaces. USA Department of Energy Contract no. DE-AC04-78CS-34293, technical progress report; 1980.
[7] Sharia AM, Rousan A, Rousan KhK, Ahmad AA. Effect of thermal conductivity of absorber plate on the performance of a solar water heater. Applied Thermal Engineering 1999;19(7):733–41.
[8] Hahne E. Parameter effects on design and performance of flat plate solar collectors. Solar Energy 1985;34(6):479.
[9] Test FL. Parametric study of flat-plate solar collectors. Energy Conversion 1976;16:23–33.
[10] Bello MB, Sambo AS. Simulation studies on pipe spacings for a collector and tank size for solar water heater. Energy Conversion Management 1992;33(3): 215.
[11] Ghamari DM, Worth RA. The effect of tube spacing on the cost-effectiveness of a flat-plate solar collector. Renewable Energy 1992;2(6):603.
[12] Holland KGT, Brugnur AP, Charalanbous PG. Optimization of the flat-plate absorber for low flow. Advances in solar energy technology. In: Proceedings of the Bionnial Congress of the International Solar Energy Society. 1987. p. 13–8.
[13] Whiller A, Saluja G. Effect of materials and constructive details on the thermal performance of solar water heaters. Solar Energy 1965;9(1):21.
[14] Mittal, Varun MK, Saini RP, Singal SK. Effective efficiency of solar air heaters having different types of roughness elements on the absorber plate. Energy 2007;32(5):739–45.
[15] Gao W, Lin W, Liu T, Xia C. Analytical and experimental studies on the thermal performance of cross-corrugated and flat-plate solar air heaters. Applied Energy 2007;84(4):425–41.
[16] Meyer BA, Mitchell JW, El-Walkil MM. Convective heat transfer in Vee-trough linear concentrators. Solar Energy 1982;28(1):33–40.
[17] Zhao XW, Li ZN. Numerical and experimental study on free convection in air layers with one surface V-corrugated. In: In. proceeding of the annual meeting of the Chinese Society of Solar Energy. 1991. p. 182–92.
[18] Stasiek JA. Experimental studies on heat transfer and fluid flow across corrugated-undulated heat exchanger surface. International Journal of Heat and Mass Transfer 1998;41(6–7):899–914.
[19] Piao Y. Natural forced and mixed convection in a vertical cross-corrugated channel. M.Sc. thesis, The University of British Columbia, Canada; 1992.
[20] Piao Y, Hauptmann EG, Iqubal M. Forced convective heat-transfer in cross-corrugated solar air heaters. ASME Journal of Solar Energy Engineering 1994;116(4):212.
[21] Noorshahi S, Hall CA, Glakpe EK. Natural convection in a corrugated enclosure with mixed boundary conditions. ASME Journal of Solar Energy Engineering 1996;118(7):50.
[22] Rabel A. Active solar collectors and their applications. Oxford university press; 1985.
[23] Andersen EE. Fundamentals of solar energy conversion. MA: Addison-Wesley Publishing Company; 1985.
[24] Hegazy A. Effect of dust accumulation on solar transmittance through glass covers of plate-type collectors. Renewable Energy 2001;22(4):525–40.
[25] Soulayman SSH. On the optimum tilt of solar absorber plates. Renewable Energy 1991;1(4):551.
[26] Colle S, Abreu SL, Glitz K, Colle F. Optimization of the auxiliary heating and water storage insulation of a low cost domestic hot water heating system with an electric shower. In: Proceedings of ISES 2001 Solar World Congress. 2001.
[27] Brinkworth BJ. Solar DHW system performance correlation revisited. Journal of Solar Energy Engineering 2001;71(4):377–87.
[28] Andres CA, Lopez JM. TRNSYS model of a thermosyphon solar domestic water heater with a horizontal store and mantle heat. Journal of Solar Energy Engineering 2002;72(2):89–98.
[29] Knudsen S, Furbo S, Shah LJ. Design of inlet to the mantle in a vertical mantle storage tank. In: Proceedings of ISES 2001 Solar World Congress. 2001.
[30] Shah LJ, Andersen E, Furbo S, Knudsen S, Heller AJ. Entrance effects in solar hot water stores. In: Proceedings of ISES 2001 Solar World Congress. 2001.
[31] Chang JM. Characteristic heat removal efficiency for thermosyphon solar water heaters during the system application phase. Journal of Solar Energy Engineering 2004;126(6):950–6.
[32] Close DT. The performance of solar water heaters with natural circulation. Solar Energy 1962;6(1):30–40.
[33] Klien SA, Beckman WA, Duffie JA. Design procedure for solar heating systems. Solar Energy Journal 1976;18(2).
[34] Lavan Z, Thompson J. Experimental study of thermally stratified hot water storage tanks. Solar Energy 1977;19(1):519.
[35] Huang BJ, Hsieh CT. A simulation method for solar thermosyphon collector. Solar Energy Journal 1985;35(1).
[36] Kabariti M, Al-Taher A. Improvement, development, and testing of domestic hot water systems. Journal of Royal Scientific Society 1988.
[37] Norton B, Probert SD. Recent advances in circulation solar energy water heater design. Applied Energy 1983;15(1):15–42.
[38] Guptha CL, Garg HP. System design in solar water heater with natural circulation. Solar Energy 1968;12(2):163–82.
[39] Zerrouki B. Effect thermosyphon, modelisation of thermocirculation. Rapport interne no.1, CDER, Algerie; 2001.
[40] Duffie JA, Beckman WA. Solar engineering of thermal process. New York: Wiley; 1980.
[41] Zerrouki A, Boumédien A, Bouhadef K. The natural circulation solar water heater model with linear temperature distribution. Renewable Energy 2002;26(4):549–59.

[42] Karaghouli AA, Alnaser WE. Experimental study on thermosyphon solar water heater in Bahrain. Renewable Energy 2001;24(3–4):389–96.

[43] Chang JM, Leu JS, Shen MC, Huang BJ. A proposed modified efficiency for thermosyphon solar heating systems. Solar Energy 2004;76(6):693–701.

[44] Belessiotis V, Mathioulakis E. Analytical approach of thermosyphon solar domestic hot water system performance. Solar Energy 2002;72(4):307–15.

[45] Henden L, Rekstad J, Meir M. Thermal performance of combined solar systems with different collector efficiencies. Solar Energy 2002;72(4):299–305.

[46] Chun W, Kang YH, Lee YS. An experimental study of the utilization of heat pipes for solar water heaters. Applied Thermal Engineering 1999;19(8):807–17.

[47] Hussein HMS, Mohamad MA, El-Asfouri AS. Optimization of a wickless heat pipe flate plate collector. Energy Conversion Management 1999;40(18):1941–61.

[48] Ismail KAR, Abogderah MM. Performance of a heat pipe solar collector. Journal of Solar Energy Engineering 1998;120(1):51–9.

[49] Oliveti G, Arcuri N. Solar radiation utilisability method in heat pipe panels. Solar Energy 1996;57(5):345–60.

[50] Pluta Z, Pomierny W. The theoretical and experimental investigation of the phase-change solar thermosyphon. Renewable Energy 1995;6(3):317–21.

[51] Schreyer JM. Residential application of refrigerant charged solar collectors. Solar Energy 1981;26(4):307–12.

[52] Soin RS, Raghuraman S, Murali V. Two phase water heater model and long-term performance. Solar Energy 1987;38(2):105–12.

[53] Esen M, Esen H. Experimental investigation of a two-phase closed thermosyphon solar water heater. Solar Energy 2005;79(5):459–68.

[54] Abreu SL, Colle S. An experimental study of two-phase closed thermosyphons for compact solar domestic hot-water systems. Solar Energy 2004;76(1–3):141–5.

[55] Joudi KA, Al-Tabbakh AA. Computer simulation of a two phase thermosyphon solar domestic hot water heating system. Energy Conversion Management 1999;40(7):775–93.

[56] Cruz MSJ, Geoffrey PH, Reis JPSA. Thermal performance of a trapezoidal-shaped solar collector/energy store. Applied Energy 2002;73(2):195–212.

[57] Chaurasia PBL. Solar water heaters based on concrete collectors. Energy Journal 2000;25(8):703–16.

[58] Naphon P, Wongwises. A review of flow and heat transfer characteristics in curved tubes. Renewable and Sustainable Energy Reviews 2006;10(5):463–90.

[59] Royds R. Heat transmission by radiation, conduction and convection. 1st ed. London, England: Constable and Co.; 1921.

[60] Colburn AP, King WJ. Heat transfer and pressure drop in empty, baffled and packed tubes. Transaction of American Institute of Chemical Engineers 1931;26:919–23.

[61] Kirov NV. Turbulence promoters in boiler smoke tubes. Journal, Institute of Fuels 1949.

[62] Nagaoka Z, Watanable A. Maximum rate of heat transfer with minimum loss of energy. In: Proceedings of 7th International Congress on Refrigeration. 1936. p. 221–45.

[63] Seigel LG. The effect of turbulence promoters on heat transfer coefficients for water flowing in horizontal tubes. Heating, Piping and Air Conditioning, ASHVE 1946.

[64] Margolis D. The effect of turbulence promoters on the rate of heat transfer and pressure drop in straight tubes. MS thesis, Lehigh University, Bethlehem, PA; 1957.

[65] Kreith F, Margoils D. Heat transfer and friction in turbulent vortex flow. Applied Scientific Research A 1959;8:457–73.

[66] Cresswell D. Mechanics of swirling turbulent flow. MS thesis, Lehigh University, Bethlehem, PA; 1958.

[67] Gambill WR, Bundy RD. An evaluation of the present status of swirl flow heat transfer. ASME 1962;62:HT42.

[68] Smithberg E, Landis F. Friction and forced convection heat transfer characteristics in tubes with twisted tape swirl generators. Transaction of ASME Journal of Heat Transfer 1964;86:39–49.

[69] Lopina RF, Bergles AE. Heat transfer and pressure drop in tape generated swirl flow of single-phase water. Transaction of ASME Journal of Heat Transfer 1969;91C:434–41.

[70] Sivashanmugam P, Sundaram S. Improved in performance of heat exchanger fitted with twisted tape. Journal of Energy Engineering 1999;125(1): 35–40.

[71] Sarma PK, Subramanyam T, Kishore PS, DharmaRao V, Sadikkakac. Laminar convective heat transfer with twisted tape in a tube. International Journal of Thermal Science 2003;42(9):821–8.

[72] Naphon P. Heat transfer and pressure drop in the horizontal double pipe with and without twisted tape insert. International Communications in Heat and Mass Transfer 2006;33:166–75.

[73] Kang YT, Stout R, Christensen RN. The effects of inclination angle on flooding in a helically fluted tube a twisted insert. International Journal of Multiphase Flow 1997;23(6):1111–29.

[74] Zimparov V. Prediction of friction factors and heat transfer coefficients for turbulent flow in corrugated tubes combined with twisted tape inserts. Part. 1: friction factors. International Journal of Heat Mass Transfer 2004;47(3): 589–99.

[75] Eiamsa-ard S, Promvonge P. Heat transfer characteristics in a tube fitted with helical screw-tape with/without core-rod inserts. International Communications in Heat Mass Transfer 2007;34(2):185.

[76] Sivashanmugam P, Suresh S. Experimental studies on heat transfer and friction factor characteristics of laminar flow through a circular tube fitted with helical screw-tape inserts. Applied Thermal Engineering 2006;26(16):1990–7.

[77] Sivashanmugam P, Suresh S. Experimental studies on heat transfer and friction factor characteristics of turbulent flow through a circular tube fitted with helical screw-tape inserts. Chemical Engineering Process 2006;46(8):1292–8.

[78] Eiamsa-ard S, Promvonge P. Enhancement of heat transfer in a circular wavy-surfaced tube with a helical-tape insert. International Energy Journal 2007;8(1):29–36.

[79] Al-Fahed S, Chamra LM, Chakroun W. Pressure drop and heat transfer comparison for both microfin tube and twisted-tape inserts in laminar flow. Experimental Thermal Fluid Sciences 1999;18(4):323–33.

[80] Chang SW, Jan YJ, Liou JS. Turbulent heat transfer and pressure drop in tube fitted with serrated twisted tape. International Journal of Thermal Sciences 2007;46(5):506–18.

[81] Sivashanmugam P, Nagarajan PK. Studies on heat transfer and friction factor characteristics of laminar flow through a circular tube fitted with right and left helical screw-tape inserts. Experimental Thermal Fluid Sciences 2007;32(1):192–7.

[82] Shah RK, London AL. Laminar flow forced convection in ducts. New York: Academic press; 1978.

[83] Gyenis J, Nemeth J. Static mixing. Magyar Kemiai Lapja 1991;46:265 [in Hungarian].

[84] Nemeth J. Static mixing. Magyar Kemiai Lapja 1995;50:473 [in Hungarian].

[85] Silapakijwongkul B, Eiamsa-ard S, Promvonge P. Effect of clockwise and counter clockwise twisted-tape turbulators on heat transfer augmentation inside a double pipe heat exchanger. In: International Conference on Energy for sustainable development: Issue and Prospect for Asia. 2006.

[86] Kumar A, Prasad BN. Investigation of twisted tape inserted solar water heaters heat transfer, friction factor and thermal performance results. Renewable Energy 2000;19(3):379–98.

[87] Rai GD. Solar Energy Utilization. India: Khanna Publishers; 1999.

[88] Jaisankar S, Radhakrishnan TK, Sheeba KN. Experimental studies on heat transfer and friction factor characteristics of thermosyphon solar water heater system with helical twisted tapes. Energy 2009;29(5–6):1224–31.

[89] Jaisankar S, Radhakrishnan TK, Sheeba KN, Suresh S. Experimental studies on heat transfer and friction factor characteristics of thermosyphon solar water heater system fitted with left–right twisted tapes. International Journal for Applied Engineering Research 2009;83(11):1943–52.